



X-band singly degenerate parametric amplification in a Josephson tunnel junction

Mygind, Jesper; Pedersen, Niels Falsig; Sørensen, O. H.

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adequate for this demonstration. Resonator volume was 150 cm^3 , maximum input power was $\sim 1 \text{ W}$, the peak surface magnetic field was $\sim 10 \text{ G}$, and frequency was 9.2 GHz .

To realize the maximum gain, the dissipation within the switch must be decreased so that $Q_e^o \geq Q_r$. In this case the gain will approach its limiting value $G \sim Q_r/Q_e^o$. From our previous analysis it follows that this requires $k_2 l \geq Q_r/Q_e^o = \tau_c/\tau_r$. Thus maximum gain requires that the relative energy loss per cycle in the switch be less than the ratio of the pulse duration τ_c to the intrinsic resonator decay time τ_r .

Present superconducting limits¹ at the X band indicate that $\tau_r \sim 10^{-1} \text{ sec}$ is achievable at high fields in Nb resonators. Maximum gain for a 100-nsec pulse from such a resonator then requires that the relative energy loss per cycle within the switch be kept less than 10^{-6} . We believe that this can be achieved, and thus that a power gain approaching 10^6 is possible. Within the switch, dissipation comes from loss in the waveguide coupling to the switch, loss in the glass discharge tube, and leakage to Z_0 . As indicated earlier, leakage has already been reduced to $\sim 10^{-5}$ and should be reduced further using superconducting components which are carefully designed. Loss in the guide is being reduced by placing a He gas discharge switch adjacent to the resonator at helium temperature and coupling via a superconducting waveguide.

A wave interference technique has been demonstrated for switching the energy stored in a superconducting resonator into an external load. The design gain of $\sim \times 10$ was achieved, producing 100-nsec pulses which are phase locked with respect to the source which feeds the resonator. It appears that the technique can be improved considerably by utilizing superconducting components for the switch itself. If the projected gain can be maintained at the high fields achieved in present day superconducting resonators, very high-power microwave pulses, which are phase locked to the low-power drive, can be generated by this technique.

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⁴A theoretical estimate indicates that the phase jitter relative to the source should be less than $R_s/(\omega\tau_c Z_0)$. Here R_s is the resistance across the gas discharge, Z_0 is the matched guide impedance, and τ_c is the decay time of the cavity when the switch is closed and it is coupled to the load. For the present case, this gives a phase jitter of less than 10^{-6} rad .

X-band singly degenerate parametric amplification in a Josephson tunnel junction

J. Mygind, N. F. Pedersen, and O. H. Soerensen

Physics Laboratory I, The Technical University of Denmark, DK-2800 Lyngby, Denmark
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Preliminary measurements on a (quasi-) degenerate parametric amplifier using a single Josephson tunnel junction as the active element is reported. The pump frequency is at 18 GHz and the signal and idler frequencies are both at about 9 GHz. A power gain of 16 dB in a 4-MHz 3-dB bandwidth is achieved at the top of the cryostat.

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Parametric amplification at microwave frequencies in Josephson junctions have recently been reported. In the case of point contacts either the internal Josephson oscillations^{1,2} or an external source³ supplied the pump power. Also arrays of unbiased microbridges⁴ and tunnel junctions⁵ have been used as the active element. In all cases the amplifiers operated in the doubly degenerate mode where the pump, signal, and idler frequencies are nearly equal ($f_p \sim f_s \sim f_i$). The singly degenerate mode where the pump frequency is about twice the signal and idler frequencies ($f_p \sim 2f_s \sim 2f_i$) was also attempted^{2,3} but gain was not achieved in this mode.

Here, we describe a singly degenerate X-band parametric amplifier using a single tunnel junction. The junction is current biased at zero dc voltage and the function

of the amplifier depends critically on the internal Josephson plasma resonance of the junction acting as a common signal and idler circuit. The advantages of the present scheme are as follows:

- (i) The amplifier properties may be tuned by means of the dc-bias current.
- (ii) The junction parameters (i.e., the plasma frequency, the rf losses, etc.) may be measured and the performance compared to theory.
- (iii) The required pump power level is lower than in the doubly degenerate mode.

Furthermore, in our opinion, a small-area tunnel junction appears potentially better suited for applica-

tions at frequencies above 100 GHz (due to the large RI_c product attainable at low temperatures) than for instance the microbridges and has favorable mechanical properties compared to the point contacts.

Parametric oscillations in the singly degenerate mode has been discussed previously theoretically⁶ and experimentally.⁷ Briefly, a tunnel junction current biased at zero dc voltage has a plasma frequency

$$f_{p1} = f_0 (\cos \phi_0)^{1/2}, \quad (1)$$

where $f_0 = (2eI_c / \hbar C)^{1/2} (2\pi)^{-1}$ is the maximum plasma frequency and $\phi_0 = \sin^{-1}(I_0/I_c)$ is the mean value of the superconducting phase. Here, C is the junction capacitance, I_c is the maximum supercurrent, and I_0 is the dc-bias current. When an external rf signal is applied at a pump frequency, f_p , subject to the condition $f_p \approx 2f_{p1}$, the threshold condition for parametric oscillations at the plasma frequency may be written⁶

$$V_{rf}(f_p) = \hbar f_p / eQ \tan \phi_0, \quad (2)$$

where $V_{rf}(f_p)$ is the rf voltage component at the pump frequency and Q is the actual quality factor of the plasma resonance. For pump levels just below the threshold a small-signal analysis⁸ shows that the junction may be represented by a negative resistance at the plasma frequency. This may give rise to amplification of applied signals at frequencies in the vicinity of f_{p1} .

In the present experiment we used a Sn-O-Sn junction with dimensions 0.1 mm × 0.2 mm, a normal-state resistance $R \sim 0.18 \Omega$, and an extrapolated current density of 20 A/cm² at $T = 0$ K. The sample configuration is shown in Fig. 1. The junction was mounted across the last section of a two-section binomial microwave transformer used to reduce the input impedance of the X-band receiver. With the mounting used here an efficient coupling between the junction and the waveguide was achieved in a bandwidth of about 100 MHz. The pump power at ~ 18 GHz was supplied to the junction by means of a very weakly coupled loop.

The X-band transmission line from the transformer to the receiver consisted of a 1-m-long stainless-steel

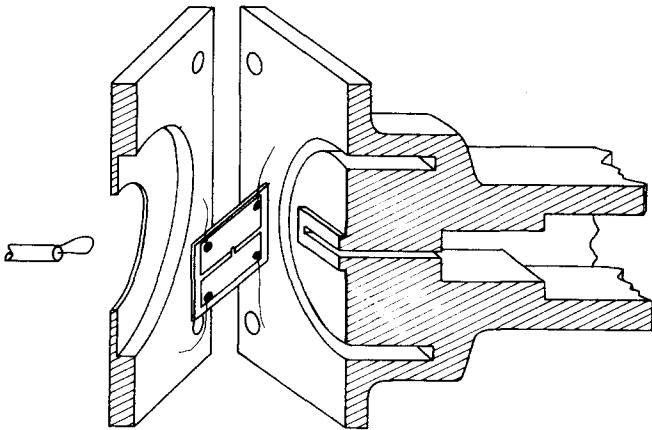


FIG. 1. A cut-away drawing of the two-step binomial microwave transformer. The junction is glued onto the end of the narrow waveguide section with a 25- μ m Mylar foil inserted for dc insulation (not shown).

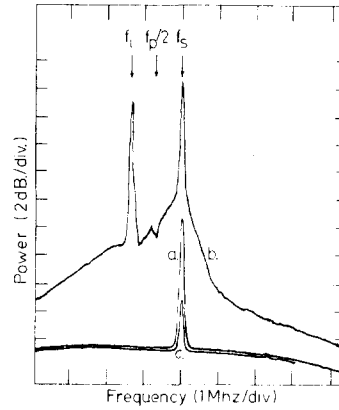


FIG. 2. A frequency display of the i.f. amplifier output. (a) shows the input signal applied directly to the receiver, trace (b) shows the signal after amplification in the junction, and trace (c) is the signal reflected from the junction in a "nonparametric" state.

waveguide, a microwave switch, a 10-dB directional coupler and, finally, a series of isolators and a 16-GHz low-pass filter. The input signal introduced through the sidearm of the directional coupler could be applied alternatively to the junction or to the receiver by operating the switch. Thus a simple determination of the gain of the reflection amplifier could be made, the gain hereby referred to the input/output terminal at the switch. The receiver was a balanced mixer followed by a 70-MHz i.f. amplifier with an overall bandwidth and noise figure of 10 MHz and 10 dB, respectively. The output of the i.f. amplifier was displayed on a spectrum analyzer.

The experimental procedure was as follows:

- (i) The helium bath temperature was adjusted such that the maximum plasma frequency f_0 was greater than the signal frequency f_s .
- (ii) The plasma frequency f_{p1} was tuned to the signal frequency (within a few MHz) by means of the dc-bias current [cf. Eq. (1)].
- (iii) The pump frequency was adjusted to $f_p \sim 2f_{p1}$.
- (iv) The pump power was increased until parametric oscillations were observed. Typically, the optimum pump power corresponded to a 5–15% suppression of the critical current.
- (v) Small readjustments of the pump power, the pump frequency, and the bias current were made in order to maximize the reflected power at the signal frequency. The optimum bias point was just below the threshold for parametric oscillations.

A typical spectral recording of the i.f. amplifier output is shown in Fig. 2. Here, the local oscillator frequency was 8.67 GHz, the signal frequency was 8.60 GHz, and the pump frequency was ~ 17.20 GHz. Curve (a) displays the input signal applied directly to the receiver. Curve (b) shows the signal after amplification in the junction. In order to maintain sufficient stability during the recording, the junction gain was set to 10 dB (small readjustments of the parameters pro-

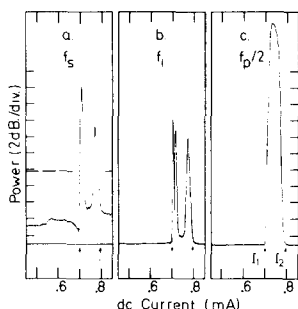


FIG. 3. The received power in a 100-kHz bandwidth centered at the frequencies f_s , f_i , and $\frac{1}{2}f_p$ versus dc bias current. The dashed line in Fig. 3(a) indicates the input power level at f_s .

duced a gain of 16 dB). Note that the idler at $f_i = f_p - f_s$ is of approximately the same magnitude as the amplified signal. Curve (c) shows the power reflected from the junction current biased outside the region of negative input resistance. Comparing curves (b) and (c) it is obvious that not only the signal but also the noise background has been amplified.

The amplitudes at the three frequencies f_s , f_i , and $\frac{1}{2}f_p$ versus dc-bias current are shown in Fig. 3. These curves were obtained by adjusting the 100-kHz window of the spectrum analyzer to coincide with either of the three frequencies while the dc-bias current was swept. Starting from Fig. 3(c) we observe that the junction emits power at $\frac{1}{2}f_p$ in a current region between I_1 and I_2 . This is however, only partly true, since the signal at currents slightly above I_1 and slightly below I_2 is in fact due to parametrically amplified noise within the bandwidth of the detector (100 kHz). Only at currents near the maximum in Fig. 3(c) the measured signal is caused by the parametric oscillations which in a frequency display is observed as a single line with a width determined by the linewidth of the pump source. Consequently, the accuracy with which the threshold for parametric subharmonic oscillations may be measured depends strongly on the input noise level. Figure 3(a) is a recording of the detected power at the signal frequency for the same range of bias currents. For currents below I_1 and above I_2 the junction is in a "non-parametric" state. As the threshold is approached from below, the magnitude of the reflected signal increases and a gain of about 10 dB is reached (the input signal level at the top of the cryostat is indicated by the dashed line in Fig. 3). By a further increase of the bias current the region of subharmonic oscillations is entered. The gain is reduced and turned into an absorption until the bias current reaches the upper threshold value where the gain tops at 6 dB. Figure 3(b) shows the idler component in the same bias current region. No idler power is emitted until the threshold is reached.

Then it varies in much the same way as the power at the signal frequency (the irregular shape of the first peak reflects an instability and is not significant).

Also the observed bandwidth depended on the bias current setting. For the setting corresponding to the highest gain (16 dB) the 3-dB bandwidth was only 4 MHz, whereas for bias adjustments corresponding to lower gain the bandwidth exceeded the i.f. amplifier bandwidth (10 MHz). With the present coupling scheme the bandwidth is always limited by the 100-MHz window of the impedance transformer. The output power was approximately linear with input power over a range $\lesssim 10$ dB and started to saturate at input power levels of order 10^{-11} W measured at the top of the cryostat.

The incoming 300 K broad-band noise strongly influenced the dynamic properties and the gain of the amplifier. Hence, a conventional noise temperature measurement produces meaningless results. We found that the signal-to-noise ratio was conserved after amplification (cf. Fig. 2) implying that in the present experimental configuration—without a cooled attenuator or circulator and filtering in the input/output waveguide—the noise figure of the parametric amplifier was comparable to that of the balanced mixer.

We have demonstrated the feasibility of a singly degenerate parametric amplifier using a single Josephson tunnel junction. A gain of 16 dB measured at the top of the cryostat was achieved at X-band frequencies. The linear range of the amplifier was of order 10 dB determined by the power handling capacity of the Josephson junction and the high level of incoming thermal noise in the present setup.

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